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PHYSICAL PHENOMENA IN CONTAINERLESS GLASS PROCESSING

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16. ABSTRACT <p>A. Arrangements were made with the Jet Propulsion Laboratory to obtain use of their 3-axis ambient temperature acoustic levitator for some of the model fluid experiments beginning with KC-135 flights in 1982 and continuing onto Shuttle flights in 1984-85.</p> <p>B. Arrangements were made with the Marshall Space Flight Center for our participation in the engineering test of a high temperature acoustic levitation facility built by Intersonics to be conducted on a Shuttle flight in late 1982.</p> <p>C. Experimental work was performed in the following areas:</p> <ol style="list-style-type: none"> 1. Experiments were conducted on bubble migration in rotating liquid bodies contained in a sphere. 2. Experiments were initiated on the migration of a drop in a slightly less dense continuous phase contained in a rotating sphere. The experiments will be continued into 1982. 3. A refined apparatus for the study of thermocapillary flow in a glass melt was built, and data were acquired on surface velocities in the melt. Similar data also were obtained from an ambient temperature fluid model. The data were analyzed and correlated with the aid of theory. 4. Data were obtained on flow velocities in a pendant drop heated from above. The motion in this system was driven principally by thermocapillarity. 5. An apparatus was designed for the study of volatilization from a glass melt. 			
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D. Theoretical work was performed in the following areas:

1. A computer model was constructed for predicting the velocity and temperature fields in a cylindrical liquid bridge. The results from the model were used for comparison with experiments, and for the correlation of experimental data.

2. A theoretical solution for the migration of a bubble in a rotating liquid body in the low Taylor number regime was obtained for comparison with experiments.

3. Work was conducted on the description of thermocapillary motion in drops of arbitrary axially symmetric shapes.

4. The problem of the quasi-static motion of a bubble eccentrically placed in a drop was solved for the axisymmetric case. Computer programs were developed for plotting streamlines and isotherms directly.

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INTRODUCTION

In this report, the progress of research in this project during the period January 1, 1981 to December 31, 1981 is described. Since the report covers a one-year period, it replaces the two semi-annual reports that normally would have been prepared to cover the same period.

The overall objective of this project is to study fluid motion and bubble behavior in a reduced gravity environment in model fluids and glass melts when such motion is the result of

- (i) interfacial tension gradients
- (ii) rotation, oscillation, etc.

The results of this research are expected to be of use in refining space-processed glasses, and in improving our understanding of the processes involved in the formation of hollow glass shells used in laser fusion.

Details on the above objectives and the applications of this work may be found in earlier reports.

During the reporting period, there were five graduate students actively associated with the project. Four are doctoral students, and the fifth, Mr. P. Kondos, at this time, is an M.S. student. Since several of the doctoral students (Messrs. Jayaraj, McNeil, and Annamalai) are expected to complete their theses in 1982, another student, Ms. Radha Sen, was recruited in the Fall of 1981. Ms. Sen already has an M.S. degree, and will take her Ph.D. qualifying examination before Summer 1982. She will work in the general area of interfacial tension gradient driven flows caused by composition gradients.

The bulk of the work in 1981 was performed on ground-based-research. This was due to a lack of availability of suitable flight hardware. However, discussions with Intersonics were initiated in the Fall of 1981 concerning the possibility of building appropriate hardware for the reduced gravity model fluid experiments on thermocapillarity. Also, arrangements were made for the participation of Clarkson personnel in a forthcoming KC-135 flight of the JPL (room-temperature) 3-axis acoustic levitator to gain experience with this equipment. This flight is scheduled to occur in April 1982. Our current plan is to conduct a portion of the model fluid experiments on bubble migration in drops in this apparatus, beginning with KC-135 flights in late 1982, and continuing on to shuttle flights in 1984-85.

In 1981, discussions also were held with the Marshall Space Flight Center concerning our participation in an engineering test flight of a high temperature acoustic levitator to be built by Intersonics. The MEA flight of this apparatus is tentatively scheduled for late 1982, and we have agreed to provide 1/4" diameter glass spheres for the purpose of tests in this hardware. It is expected that the returned sample(s) from flight will provide some information on the behavior of a glass melt under reduced gravity conditions. However, due to possible uncontrolled sample rotation that might occur in this experiment, the results probably will be more useful in designing future experiments, than be of immediate scientific value.

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The following papers based on research supported by the MPS program were published, accepted for publication, or submitted during the reporting period. Copies of all the published articles are attached as Appendix A.

Published During Reporting Period

1. Subramanian, R.S., "The Slow Migration of a Gas Bubble in a Thermal Gradient," AIChE Jl., 27, No. 4, 646-654 (1981).
2. [†] Subramanian, R.S., and M.C. Weinberg, "Asymptotic Expansions for the Description of Gas Bubble Dissolution and Growth," AIChE Jl., 27, No. 5, 739-748 (1981).
3. [†] Weinberg, M.C., and R.S. Subramanian, "The Dissolution of a Stationary Bubble Enhanced by Chemical Reaction," Chem. Engng. Sci. 36, No. 12, 1955-1965 (1981).
4. ^{*} Meyyappan, M., W.R. Wilcox, and R.S. Subramanian, "Thermocapillary Migration of a Bubble Normal to a Plane Surface," J. Colloid Interface Science 83, No. 1, 199-208 (1981).
5. Shankar, N., R. Cole, and R.S. Subramanian, "Thermocapillary Migration of a Fluid Droplet Inside a Drop in a Space Laboratory," Int. J. Multiphase Flow 7, No. 6, 581-594 (1981).

Accepted for Publication During Reporting Period

1. Jayaraj, K., R. Cole, and R.S. Subramanian, "Combined Thermocapillary and Buoyant Flow in a Drop in a Space Laboratory," J. Colloid Interface Science, in press, 1982.
2. Jucha, R.B., D. Powers, T.J. McNeil, R.S. Subramanian, and R. Cole, "Bubble Rise in Glass Melts," J. Amer. Ceram. Soc., in press, 1982.

Submitted for Publication During Reporting Period

1. Annamalai, P., R.S. Subramanian, and R. Cole, "Bubble Migration in a Rotating Liquid-Filled Sphere," Phys. of Fluids, Submitted for publication, June 1981.
2. Shankar, N., and R.S. Subramanian, "The Slow Axisymmetric Thermocapillary Migration of an Eccentrically Placed Bubble Inside a Drop in a Space Laboratory," J. Fluid Mechanics, submitted for publication, October 1981.

[†] Research performed while R.S. Subramanian was on sabbatical leave at Jet Propulsion Laboratory.

^{*} Related research supported by the MPS program through a subcontract from Westinghouse R & D Center.

The following papers were presented at various meetings during the reporting period. Several of the papers were or will be included in the proceedings of the various symposia where they were presented. These are marked by a dagger.

1. Subramanian, R.S., "The Thermocapillary Migration of a Bubble in a Large Body of Liquid," European Mechanics Colloquium 138, Karlsruhe, West Germany, March 1981.
2. Shankar, N., M. Meyyappan, R. Cole, W.R. Wilcox, and R.S. Subramanian, "Some Interaction Effects in Thermocapillary Bubble Migration," European Mechanics Colloquium 138, Karlsruhe, West Germany, March 1981 (Poster Presentation).
3. McNeil, T.J., R. Cole, W.R. Wilcox, and R.S. Subramanian, "An Investigation of Surface Tension Driven Flows in Glassmelts," American Ceramic Society 83rd Annual Meeting, Washington, D.C., May 1981.
4. †Annamalai, P., N. Shankar, R. Cole, and R.S. Subramanian, "Bubble Migration Inside a Liquid Drop in a Space Laboratory," Symposium on Mechanics and Physics of Bubbles in Liquids, California Institute of Technology, California, June 1981 (Proceedings to be published in Applied Scientific Research, 1982).
5. Subramanian, R.S., and R. Cole, "Transport Phenomena in Space Processing," Society of Engineering Science 18th Annual Meeting, Brown University, Rhode Island, September 1981.
6. †McNeil, T.J., R. Cole, W.R. Wilcox, and R.S. Subramanian, "Thermocapillary Convection in a Cylindrical Zone," International Chemical Engineering Congress, Montreal, Canada, October 1981.
7. †Jucha, R.B., D. Powers, T.J. McNeil, R.S. Subramanian, and R. Cole, "Bubble Rise in Glassmelts," International Chemical Engineering Congress, Montreal, Canada, October 1981.
8. †Jayaraj, K., R. Cole, and R.S. Subramanian, "Thermocapillary Convection in Pendant Drops," International Chemical Engineering Congress, Montreal, Canada, October 1981 (Poster Session).
9. †Meyyappan, M., W.R. Wilcox, and R.S. Subramanian, "The Migration of Gas Bubbles in a Thermal Gradient -- Interaction Effects," International Chemical Engineering Congress, Montreal, Canada, October 1981 (Poster Session).
10. †Shankar, N., R. Cole, and R.S. Subramanian, "Thermocapillary Migration of a Gas Bubble Inside a Liquid Drop in a Space Laboratory," International Chemical Engineering Congress, Montreal, Canada, October 1981 (Poster Session).

† Published, or to be published, in Conference Proceedings

11. †Annamalai, P., R.S. Subramanian, and R. Cole, "Bubble Migration in a Rotating, Liquid-Filled Sphere: Application to the Formation of Hollow Glass Laser Fusion Targets," International Chemical Engineering Congress, Montreal, Canada, October 1981 (Poster Session).
12. Shankar, N., R. Cole, and R.S. Subramanian, "Thermocapillary Migration of a Gas Bubble Eccentrically Located Inside a Liquid Drop," AIChE 74th Annual Meeting, New Orleans, Louisiana, November 1981.
13. Jucha, R.B., D. Powers, T.J. McNeil, R.S. Subramanian, and R. Cole, "Bubble Rise in Glass Melts," AIChE 74th Annual Meeting, New Orleans, Louisiana, November 1981.
14. †Shankar, N., P. Annamalai, R. Cole and R.S. Subramanian, "The Motion of Bubbles Inside Drops in Containerless Processing," International Colloquium on Drops and Bubbles, Monterey, California, November 1981 (Poster Session).
15. †Meyyappan, M., W.R. Wilcox, and R.S. Subramanian, "Interaction Effects in Thermocapillary Bubble Migration," International Colloquium on Drops and Bubbles, Monterey, California, November 1981.
16. †McNeil, T.J., R. Cole, and R.S. Subramanian, "Surface-Tension Driven Flow in Glassmelts and Model Fluids," Materials Research Society Annual Meeting, Boston, Massachusetts, November 1981.
17. †Annamalai, P., R.S. Subramanian, and R. Cole, "Bubble Motion in a Rotating Liquid Body," Materials Research Society Annual Meeting, Boston, Massachusetts, November 1981.
18. †Meyyappan, M., R.S. Subramanian, W.R. Wilcox, and H.D. Smith, "Bubble Behavior in Molten Glass in a Temperature Gradient," Materials Research Society Annual Meeting, Boston, Massachusetts, November 1981.
19. †Shankar, N., R. Cole, and R.S. Subramanian, "Thermocapillary Motion of Bubbles Inside Drops," Materials Research Society Annual Meeting, Boston, Massachusetts, November 1981.
20. †Smith, H.D., D.M. Mattox, W.R. Wilcox, R.S. Subramanian and M. Meyyappan, "Experimental Observation of the Thermocapillary Driven Motion of Bubbles in a Molten Glass under Zero Gravity Conditions," Materials Research Society Annual Meeting, Boston, Massachusetts, November 1981.

The research conducted by the four doctoral students, Messrs. P. Annamalai, K. Jayaraj, T.J. McNeil, and N. Shankar, and the M.S. student, Mr. Kondos, on their ongoing thesis projects during the reporting period is summarized below. Ms. Sen has been spending her time principally in becoming familiar with the pertinent literature on her thesis topic: "Flows Driven by Interfacial Composition Gradients."

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THE MIGRATION OF A BUBBLE/DROPLET IN A ROTATING LIQUID

P. Annamalai

The objective of this project is to study, both experimentally and theoretically, the motion of a bubble/droplet in a rotating liquid body.

A theoretical model of bubble migration in a rotating liquid was constructed and the equations solved in the limit of low values of the Taylor number. Suitable experiments on the motion of bubbles in silicone oils contained in rotating spheres were performed to verify the principal predictions of the theory. A preliminary comparison of theoretical trajectories and asymptotic bubble locations with those observed in the experiments was made. Details may be found in Appendix B-1 which contains a copy of the paper by Annamalai et al. on this subject which was presented at the Boston meeting of the Materials Research Society held in November 1981.

An experimental study of drop migration in a rotating liquid system yielded the surprising observation that, under certain conditions, the heavier (water) drop actually migrated toward the rotation axis, and reached a stable position near the axis at low rotation rates. At higher rates, the drop was found to leave this position, and migrate toward the boundary. The observations were found to be reproducible, and were confirmed with other combinations of a heavy drop in a lighter continuous medium. More quantitative experiments on this new phenomenon are now underway.

THERMOCAPILLARY CONVECTION IN DROPS

K. Jayaraj

The objective of this research is to study thermocapillary motion in drops both experimentally and theoretically.

The bulk of the effort during the year was spent on refining the experimental apparatus, and acquiring data. The apparatus was described in the last semi-annual report. It consists of a thermocouple junction from which a pendant drop of a suitable fluid is suspended. The drop is heated from above by conducting heat through the thermocouple lead wires, and illuminated in a meridian section by means of a 50 μ m sheet of laser light. Lycopodium particles serve as tracer material. Provisions are available to make video or motion picture records of the drop during the experiment through a microscope. The data are analyzed using an X-Y indicator or a motion analyzer connected to a microprocessor.

The initial efforts at measuring velocities were confined to the use of a stopwatch and a calibrated reticle in the microscope eyepiece. These results were reported in a paper presented in October in Montreal at the Second World Congress on Chemical Engineering. The paper by Jayaraj et al., included in the proceedings of that meeting, is attached as Appendix B-2, and may be consulted for additional details.

Subsequent to the above work, motion picture records were made using a Bolex movie camera. These data are still being analyzed. Also, video recordings of the motion in the drop have been made, and will be analyzed in 1982.

The theoretical work on the motion in a spherical drop due to the combined action of buoyancy and thermocapillarity discussed in the last report was submitted for publication in the Journal of Colloid and Interface Science. It was accepted, and is scheduled to appear in 1982.

Efforts spent on extending the theory to arbitrary axisymmetric shapes via collocation methods have not been successful so far. The principle source of difficulty appears to be in the use of poorly converging series in Legendre Polynomials in the collocation procedure. In 1982, the difficulties will either be resolved or alternative methods of solution such as complete numerical integration of the field equations will be pursued.

VOLATILIZATION IN GLASS MELTS

P. Kondos

The objective of this research is to study experimentally the kinetics of volatilization from glass melts.

In the first phase of this work, a detailed search of the pertinent literature was made. The literature search revealed the following,

(1) The process of volatilization in even a "simple" binary glass is not completely understood. Detailed information on the nature of the species evaporating from a binary melt such as sodium borate at various temperatures and compositions is not available.

(2) Information on equilibrium partial pressure versus temperature for the various species in multicomponent glass melts is not generally available. Some data on pure component vapor pressures exist. However, the solutions formed in multicomponent melts are probably nonideal.

(3) No attempt has been made in the experiments conducted by others so far to control the fluid mechanical conditions in the surrounding gas phase or in the glass melt. Thus, empirical parameters are introduced into "models" to account for buoyant convective transport in the gas phase. Buoyant motion in the melt is usually ignored. Such parameters obscure the interpretation of experiments.

(4) Typical experiments in the past have involved the weighing of crucibles containing glass samples exposed to a specified furnace temperature for various periods. This procedure can introduce mixing in the melt when it is disturbed, a process ignored in the "diffusion" models used to interpret the data.

In view of the above, a conceptual experiment was designed in our laboratory for the study of volatilization wherein some of the above shortcomings of previous investigations could be overcome. The essence of the experimental idea is to suspend a drop of glass melt in a controlled forced-convection environment inside a transparent furnace, and to monitor both its size and its mass as functions of time. From this data, important information on the kinetics of volatilization can be extracted with the use of suitable transport models.

All of our effort in 1981 in this project was spent in constructing a suitable apparatus for the above experiment. Experimental problems still remain

in the area of long-term stability in the microbalance used for the measurement of the weight of the drop as a function of time, and in the measurement of the drop size using microscope techniques.

Our plans for 1982 at this time are for completing the initial phase of the experimental study of volatilization phenomena using sodium borate as a candidate material.

THERMOCAPILLARY CONVECTION IN MODEL FLUIDS AND GLASS MELTS

T. J. McNeil

The objective of this research is to study thermocapillary motion in glass melts as well as in model fluid systems.

The experimental systems used for the study are small cylindrical liquid bridges held between vertical rods. The apparatus and procedure have already been detailed in the last semi-annual report.

Considerable effort was spent during the year 1981 in refining the apparatus for the glass melt studies which employed a transparent furnace. After several attempts to eliminate problems associated with undesirable bubble nucleation in the melt, the solution was found. Graphite end rods were used with a sodium borate melt, and the problem was eliminated. Surface velocities in the melt were measured using diamond dust as a tracer. A stopwatch and a calibrated reticle in the microscope eyepiece were used for the velocity measurements. The Reynolds and Marangoni numbers were varied over as wide a range as possible. Suitable model fluid experiments also were performed using Dow-Corning DC-200 silicone oils.

A theoretical model of the system was constructed. The governing conservation equations along with the associated boundary conditions were solved using the method of finite differences.

Some of the results from the theory and the experiments were presented at the Materials Research Society meeting in Boston held in November. A paper prepared for inclusion in the proceedings of that meeting is attached (Appendix B-3) and may be consulted for details.

A doctoral thesis based on this research was prepared in late 1981. It will be defended shortly.

The above research focused on the development of an apparatus for the study of thermocapillary flow in a high temperature melt. Many important and interesting experiments on the actual flow still remain to be performed. These include the study of the influence of composition in binary and multicomponent melts, and the study of melts exhibiting a positive coefficient of surface tension with temperature. Also, the range of Marangoni numbers can be extended by the use of video or motion picture techniques for recording motion in the system. It is expected that in 1982 or '83, a new graduate student will be recruited to continue this effort.

THERMOCAPILLARY MOTION IN BUBBLES INSIDE DROPS

N. SHANKAR

The objective of this work is to develop theoretical models to describe bubble motion inside a drop when a known temperature field is prescribed on the drop surface.

The year 1981 was spent completing the theoretical calculations for the axisymmetric motion of a bubble eccentrically located inside a drop. Computer programs were developed for calculating the results for the temperature and the streamfunction fields as well as the bubble migration velocity as a function of system parameters. Graphics routines were developed so that streamlines and isotherms could be plotted directly on a plotter connected to the College computer. A manuscript based on this work was submitted for publication, and is under review at this time. Some details are given in Appendix B-4 which is a copy of the paper presented at the Boston meeting of the Materials Research Society.

Efforts were begun on extending the theory to account for the deformation of the shape of the drop. This topic will be pursued actively in 1982.

APPENDIX A

Publications in Journals in 1981

APPENDIX B

Some Pertinent Proceedings Papers

Copies of the publications and proceedings listed under Appendix A and Appendix B in the Table of Contents may be obtained from:

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